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FRACTURE TOUGHNESS ASSESSMENT ON THE GIRTH WELDED JOINT OF AN API X70 STEEL TUBE

Vitor Scarabeli Barbosa[1]
engmat.vsb@gmail.com

Marcelino Pereira do Nascimento[1]
pereira@feg.unesp.br

Luis Rogerio de Oliveira Hein[1]
rhein@feg.unesp.br

Thierry Henrique Machado Gumieri[1]
tgumieri85@yahoo.com.br
[1]UNESP – Univ. Estadual Paulista, DMT – Department of Materials and Technology, Av. Ariberto Pereira da Cunha, 333, Guaratinguetá, SP, 12.516-410, Brazil.

Abstract. *Studies about structural integrity are very important when it desires to prevent disasters associated with the failure of materials. The welded joints in pipeline steels used for transportation of oil and gas correspond to the regions most susceptible to flaw. The current study was developed to assess the structural integrity of a steel pipe API 5L X70 used in pipeline systems. This assessment was performed by means of CTOD (Crack Tip Opening Displacement) methodology. The tests were performed in SE(B) – Single Edge Bend - specimens extracted from girth welded joint obtained by GTAW (Gas Tungsten Arc Welding) process in the root pass and FCAW (Flux Cored Arc Welding) process in the subsequent passes (filling and finishing) and the base metal 90° from the welded joint of the tube. Samples were extracted from L-C direction relative to the longitudinal axis of the pipe. The purpose was simulate in the laboratory the loading under actual conditions of use of the product and investigate the fracture toughness in the regions mentioned previously. Sought to compare the results of CTOD calculated by standard ASTM E 1820 (2008) and BS 7448 (1991) and it was found that the values of CTOD tend to converge to a common value.*

Keywords: *structural integrity, failure, welded joints, CTOD.*

1. INTRODUCTION

Long-distance high-pressure pipelines are considered as the most economical mode of transportation of the crude oil and gas from the production site to the end users (Datta and Deva, 2002; Li *et al*., 2011; Hashemi, 2009).

In recent years, the driving force for pipeline design has been due the higher consumption and hence higher demand for transportation capacity and sufficient safety (*i.e.* avoiding premature failure of pipeline during service) (Datta and Deva, 2002). This increasing demand has led to mass production and improvement of high-strength low-alloy (HSLA) steels in recent years (Hashemi, 2011).

High-strength low-alloy (HSLA) microalloyed steel pipelines are becoming more popular as the material of choice for large pipeline projects because of the advantages they provide such as reduced quantity of steel required and therefore reduced welding and installation costs, low price-to-yield ratio and low carbon content which impact material (Moeinifar, 2011a; Al-Mansour, 2009; Hillenbrand, 2004).

The high strength low alloy pipeline steels essentially require excellent combination of strength, toughness and weldability (Hashemi, 2011; Beidokhti *et al*., 2009a; Shin, *et al*., 2006; Li *et al*., 2011; Beidokhti *et al*., 2009b). Furthermore, formability, fracture toughness, low ductile to brittle transition temperature (DBTT) are additional requirements for oil and gas transmission through steel pipelines in order to improve the transportation efficiency and ensure safety over a long distance under high pressure (Hashemi and Mohammadyani, 2012; Beidokhti *et al*., 2009c; Sung *et al*., 2012; Wang *et al*., 2009). According to (Hashemi, 2011; Hashemi 2009) the pipeline systems are undergo a high internal pressure that can overtake 80% of their minimum specified yield strength (MSYS). Therefore, in order to ensure the integrity of pipeline, the properties aforementioned are vital for pipeline structures, which are vulnerable to plastic collapse and to ductile crack propagation.

The pipe technical specifications are given by standard codes, such as API (American Petroleum Institute) and DNV (Det Norske Veritas). The pipeline steels have been denominated as API X65, API X70, etc., based on strength in accordance with the API specifications. The API X70 steels refers to steel grade with 70 ksi or 485 MPa nominal yield strengths in accordance with standard API 5L code (Hashemi, 2011; Kim *et al*., 2007; API 5L 44th, 2008).

A fracture toughness test measures the resistance of a material to crack extension. Such a test may yield either a single value of fracture toughness or a resistance curve, where a toughness parameter such as K, J or CTOD is plotted against crack extension (Anderson, 1995).

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According to (Shin, *et al*., 2006) to assess fracture properties of pipeline steels, several laboratory-scale testing methods, for instance Crack Tip Opening Displacement (CTOD), which correspond closely with full-scale fracture behavior have been analyzed. Thereby a reliable fracture control methodology is required to ensure the safety and structural integrity of these piping systems in the case of an unlikely burst event (Hashemi, 2008). Since they should be welded to make large-scale pipelines, welding is an indispensable process for them (Sung, *et al*., 2011). From this idea, this work aims to simulate the welding conditions for the manufacture of industrial pipes, made in boiler shops (pipe-shop) within petrochemical plants. According to (Gumieri, 2011) these pipes are often undergo to operation with flammable and toxic fluid subjected to high pressures and temperatures, where one can break the line can cause irreparable damage to the plant, the environment and the health of surrounding communities. The intention with this study is to evaluate whether the weld metal has the similar properties such as fracture toughness compared to the base metal. This study highlights the importance of using a qualified welding procedure for performing quality welds while ensuring the properties of the fracture toughness of the weld metal.

Lately due the higher requirement of operation and safety, the fracture toughness has shown the main concern in the design of oil and gas pipelines (Moienifar, *et al*., 2011a; Moienifar, *et al*., 2011b).

Experimental observations consistently reveal that the fractures initiates from surface defects, *e. g.* corrosion, fatigue damage or weld defects (*e. g.*, lack of penetration, undercut, porosity and entrapped slag) and progress through the wall thickness and in the longitudinal direction, to eventually propagate in an unstable fashion when their length exceeds a critical value (Paredes and Ruggieri, 2012; Hashemi, 2008). This critical value can be assessed by CTOD methodology, where samples notched and pre-cracked undergo static stress to measure the materials toughness in presence of a crack. According to (Paredes and Ruggieri, 2012) these approaches allow the specification of critical crack sizes based on the predicted growth of crack-like defects under service conditions.

According to (Li and Baker, 2009; Amirat, *et al*., 2006; Moienifar, *et al*., 2011b; Sung, *et al*., 2011) during the manufacturing process of the pipe and its installation, due to the influence of a welding thermal cycle and mechanical deformations the toughness of high-strength low-alloy (HSLA) steels generally can be damaged by causes aforementioned. Other critical factor caused by the welding thermal cycle is the increase on the ductile-brittle transition temperature. At low temperatures, this degradation has been attributed to the formation of local brittle zones in the welded joint that can lead to a brittle failure.

In a recent work (Beltrão *et al*., 2012) observed that the fatigue cracks nucleation and propagation has been observed with higher frequency at welded joints in pipeline steels, due to presence of welding inclusions and defects that acts as stress concentrator, factors these which also contributes for toughness decrease.

Fracture toughness of steels in the ductile to brittle transition temperature region can be evaluated by measuring plane stress fracture toughness (CTOD) in accordance with the ASTM E1820 standard test method.

In this study, fracture toughness at room temperature of an API X70 pipeline steels was analyzed in accordance with the ASTM E1820-08 and BS 7448-1991 standard test method. Based on the reference temperature that characterizes fracture toughness at room temperature, fractographic studies were carried out to determine the fracture features of the CTOD fractured specimens.

2. TEST MATERIAL AND EXPERIMENTAL PROCEDURE

2.1 Material

The material under investigation was API 5L-X70 grade pipeline steel with 203.2 mm outside diameter (OD) and 15.1 mm wall thickness (WT). Chemical composition of experimental steel is given in Table 1. The mechanical properties of the pipe were measured using tensile bars obtained from pipe. The API X70 steel is one of the most commonly used pipe material in Brazil high-pressure oil and gas transportation.

Table 1. Chemical composition of experimental steel (mass percent, %) with delivery condition M (thermo-mechanical formed or rolled.

Steel Grade	Mass fraction, based upon heat and product analyses % maximum									Carbon equivalent % maximum
	C	Si	Mn	P	S	V	Nb	Ti	Other	Pcm
API 5L X70	0.12	0.45	1.70	0.025	0.015	[a]	[a]	[a]	[b]	0.25
DNV-0S SMYS 485	0.12	0.45	1.75	0.020	0.010	0.10 [a]	0.08 [a]	0.06 [a]	[b]	0.22
Experimental X70	0.10	0.16	1.34	0.008	0.0013	0.059	0.0505	0.0078	matched	0.1984

[a] Unless otherwise agreed, the sum of the niobium, vanadium and titanium concentrations shall be ≤ 0.15 %.

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[b] Unless otherwise agreed, 0.50 % maximum for copper, 0.50 % maximum for nickel, 0.50 % maximum for chromium, 0.50 % maximum for molybdenum and boron ≤0.0005%.

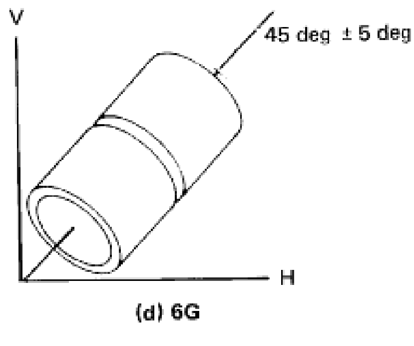
2.2 Welding procedure of pipeline

The API 5L-X70 pipeline steel were girth welded by welding process GTAW (Gas Tungsten Arc Welding) in the root pass and welding process FCAW (Flux Cored Arc Welding) in the subsequent passes (filling and finishing). The parameters and consumable materials for the welding process are listed in Table 2.

Table 2. The parameters and consumable materials of the welding process (Gumieri, 2011).

Pass Nº	Layer Nº	Grading Consumables	Ø (mm)	Voltage (V)	Current (A)	Speed (mm/min.)	Oscillation (mm)	Temperature (ºC)	Heat Input (J/mm)	Gas Output (l/min)
1	1	ER70S-3	3.2	10	106	77.50	4	54	820.65	12
2	2	ER70S-3	3.2	11	145	133.30	4	125	717.93	12
3	3	E81T8Ni2J	2	21	262	182.50	5	130	1808.9	12
4	3	E81T8Ni2J	2	22	268	137.33	5	148	2576	13
5	4	E81T8Ni2J	2	19	225	146.23	5	148	1754.1	13
6	4	E81T8Ni2J	2	20	208	131.20	5	150	1902.4	13
7	4	E81T8Ni2J	2	20	202	166.80	5	152	1453.2	13
8	**5**	E81T8Ni2J	2	21	213	183.00	4	150	1466.6	13
9	**5**	E81T8Ni2J	2	21	217	192.40	4	152	1421.1	13
10	**5**	E81T8Ni2J	2	22	223	201.70	5	147	1459.4	13

The girth weld was carried out at 6G position in according with QW 461.4 from ASME Section IX as can be seen in Fig.1. The purpose of this welding position was to hinder the welding process of the welder in order to simulate the worst field conditions that can occur during the girth welding.



(a)

(b)

Figure 1: (a) Schematic presentation of welding position "6G" – (ASME Sec. IX, 2010, p.153); (b) Welding simulation of test pipe (Gumieri, 2011).

2.3 Tensile tests

In this research, two longitudinal pipe body tensile specimens were used to measure mechanical properties of API X70 steel, as recommended by API code. A central objective of tensile test was determined the tensile strength of weld metal and compared with requirements for the base metal set by API 5L standard code. The test samples were cut from pipe in the specified position and direction, as shown in Figure 2. Tensile tests were carried out conformed to ASME Section IX requirements. All tests were carried out at room temperature.

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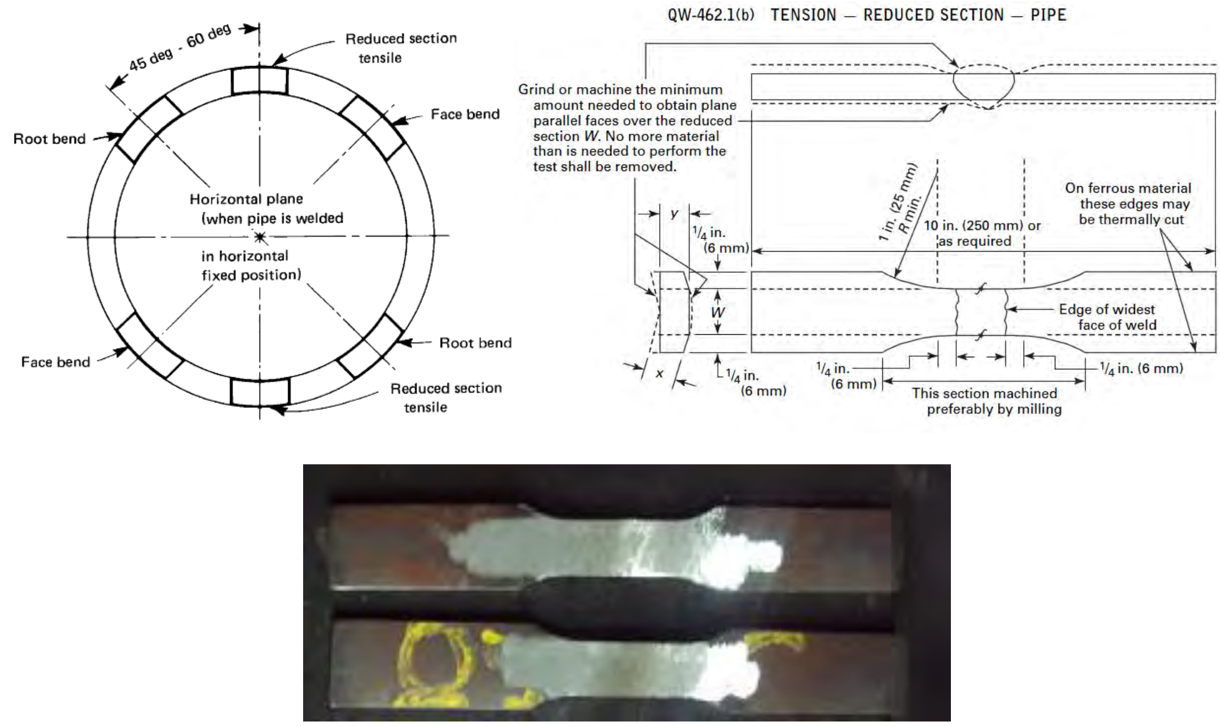

Figure 2: Schematic illustration: (a) location and orientation of pipe body tensile samples (ASME Sec. IX, 2010, p.179); (b) dimensions of tensile specimens used for weld metal testing (ASME Sec. IX, 2010, p.158); (c) samples for tensile test (Gumieri, 2011).

2.4 Tests of toughness CTOD

After welding simulation of test pipe, single edge notch bend (SE(B)) specimens were cut from pipe in the specified position and direction, as shown on the sketch in Figure 3.

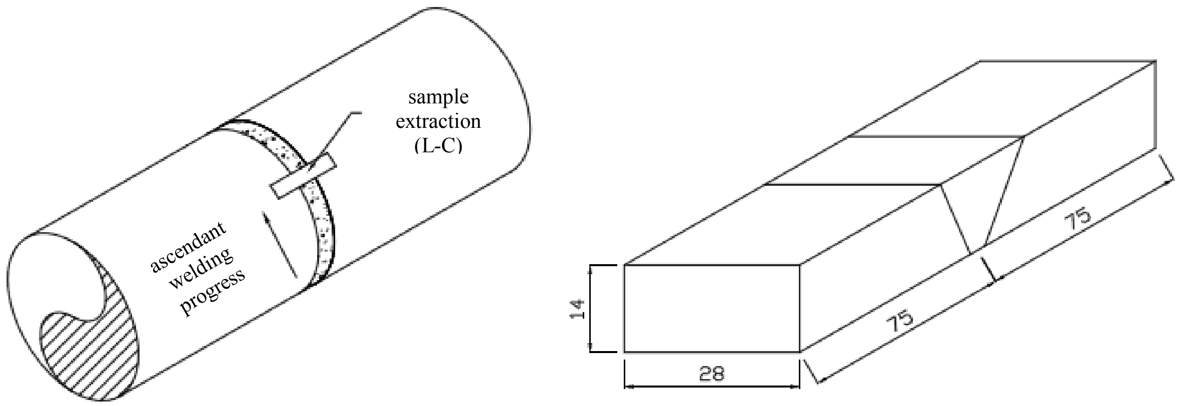

Figure 3: (a) Location and orientation of CTOD samples (Gumieri, 2011); (b) Design and dimension of CTOD samples (Gumieri, 2011).

The only specimen size requirement of the British and ASTM CTOD standards is a recommendation to test full section thickness. As can be seen from the Fig. 3(a), the specimens were cut in the longitudinal-circumferential (L-C) direction. According to ASTM E1820 - 08 fatigue precracking is required for producing a sharp crack for all specimens. The specimens were fatigue pre-cracked using an Instron 8801 Servohydraulic upon a sinusoidal constant amplitude load, load ratio R = 0.1, at 15 Hz frequency and room temperature, according to ASTM E1820-08. The specimen's dimensions from base metal (MB) and weld metal (WM), as can be seen from Fig. 3(b), were undergo three point bending test according shown Figure 4(a) and 4(b).

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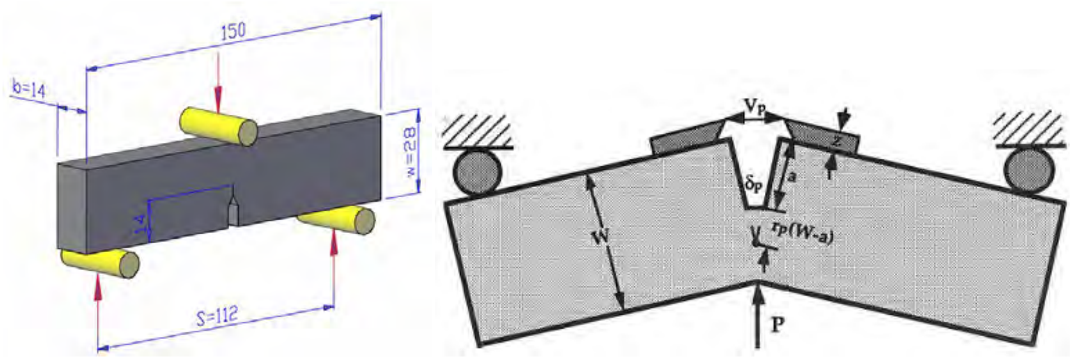

Figure 4: (a) Schematic of CTOD test and specimen's dimensions (Gumieri, 2011); (b) Hinge model for plastic displacement in a SENB specimen (Anderson, 1995).

This test was carried out to characterizes the fracture toughness of an API 5L X70 steel, using SE(B) specimens for CTOD determination in two configurations: notches located in the base metal (BM) and in the weld metal (WM). The specimens dimensions, shown in Fig. 4(a), were thickness B=14mm, width W=28mm, span S=112mm and crack length to width ratio (a/W) of 0.5, according to BS7448 standard. It was used a knife edge of 1.6 mm thickness.

Experimental CTOD estimates are made by separating the CTOD into elastic and plastic components, similar to the J_{IC} and J-R tests. Thereby, the total CTOD (δ) value is divided in two components: elastic component (dependent of the stress intensity factor - K) and plastic component (as a function of plastic component displacement (CMOD) - Vp), Eq. (1). These two components are dependent of specimen's dimensions.

BS7448-based CTOD, δ(BS), is calculated using the plastic component of CMOD, Vp, in Eq. (2):

$$\delta_{BS} = \delta_{el} + \delta_{pl} \tag{1}$$

$$\delta_{BS} = \left[\frac{F.S}{B.W^{1,5}} . f\left(\frac{a_0}{W}\right)\right]^2 . \frac{(1-\nu^2)}{2.\sigma_{YS}.E} + \frac{r_p.(W-a_0).V_p}{0,4.W+0,6.a_0+z} \tag{2}$$

In the Equation (1), δel is the elastic component of CTOD and δpl is the plastic component of CTOD as mentioned previously. The following parameters are described as: (K) is the stress intensity factor for the critical load, (ν) is Poisson's ratio, (E) is Young's modulus and (σys) is the yield strength of the material at the interest temperature. The following dimensions are described as: (W) is the width, (B) is the specimen thickness, (a_0) is the initial crack length, (W-a_0) is the remaining ligament or uncracked ligament and (z) is thickness of knife-edge to put the clip gauge. All this parameters are shown in Fig. 4(b). The factor of (r_p) gives the location of the rotational center in the plastic hinge model, and basically depends on the relative crack depth, a_0/W, as illustrated in Figure 4(b). It is interesting to mention that BS7448 standard has adopted r_p = 0.4 for three point bend specimens.

On the other hand, ASTM-based CTOD, δ(ASTM), is obtained using the plastic area under a load versus crack mouth opening displacement curve, (Ap), as shown in Eq. (4). In an analogous manner in Eq. (1) the total CTOD (ASTM) value can also be separated into an elastic and a plastic component as shown in Eq. (3). For the single edge bend specimen, calculations of CTOD are made from the following expression:

$$\delta_{ASTM} = \frac{1}{m.\sigma_Y} . (J) = \frac{1}{m.\sigma_Y} . (J_{el}+J_{pl}) \tag{3}$$

where:

Jel = elastic component of J, and
Jpl = plastic component of J

$$\delta = \frac{1}{m.\sigma_y} . \left\{\frac{K^2.(1-\nu^2)}{E} + \left[\frac{\eta.A_p}{B.(W-a_0).(1+\frac{\alpha+z}{(0,8.a_0+0,2.W)})}\right]\right\} \tag{4}$$

According to the Eq. (4) η is the plastic eta factor calculated using a_0/W. The British CTOD standard allows a_0/W ratios ranging from 0.45 to 0.55, while the ASTM standard restricts the permissible a_0/W values to the range of 0.45 to 0.70 for δ determination. J in the parentheses in Eq. (3) is converted to δ(ASTM) using mσY, where σY is the effective yield strength, which is the average of σys and the tensile strength, σts. According to ASTM E1820-08 calculation of δ requires σys/σts ≥ 0.5. The parameter (m) is the constraint factor whose equation is given by ASTM E1820-08 standard.

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2.5 Fractographic Analyses

In the present work, fracture surfaces of each CTOD specimen condition were observed by a scanning electron microscope (SEM) in order to analyze the fracture surface morphology and identification of main fracture micromechanisms operating during the crack propagation in the material.

3. RESULTS AND DISCUSSIONS

The mechanical properties of API X70 steel obtained from pipeline longitudinal samples, in accordance with ASTM E 8M, are set out in Table 3. As can be seen from this data, both samples show yield strengths over 485 MPa (70 ksi), satisfying the strength requirement of API X70 grade pipeline steels set by API 5L 44th .

Table 3. Room-temperature tensile properties of API X70 steel in the longitudinal direction and target values specified by API 5L.

Pipe grade	Tensile properties				
	Yield Strength (YS)		Tensile Strength (TS)		Ratio (Y/T)
L485Q or X70Q	Minimum	Maximum	Minimum	Maximum	maximum
L485M or X70M	485	635	570	760	0.93
Sample 1	510.63		638.29		0.80
Sample 2	536.35		619.24		0.87

Welding safety procedures it should result in welding joints containing mechanical properties and toughness similar to the base metal (strength evenmatch requirement). However, to reduce the likelihood of structural failure caused by an undetected weld defect or by a weld flaw formed during operation, many current practices and codes of manufacture (e.g., ASME and AWS) require the use of weldments with weld metal mechanical strength higher than the base metal; a condition referred to as overmatching (Donato, *et al*., 2008; Paredes and Ruggieri, 2012).

The main purpose of overmatch requirement is secure the welded joint integrity of the potential deleterious effects defects often found in the weld metal. As can be shown in Fig. 5, both tensile samples were fractured in the base metal, thereby can be stated that the weld metal properties is higher than base metal. This condition is well known as weld overmatch, according to the aforementioned. In this case, the strain can be concentrated in the base metal that has normally shown higher toughness than the weld metal.

Figure 5: Tensile samples broken at the base metal.

The fracture toughness tests were carried out using an Instron 8801 Servohydraulic Fatigue Testing System up to 100 kN with a loading rate corresponding to the constant crack head displacement of 02 mm/min at room temperature. A clip-gage was placed in the top of the notch in the knife edges and monitored its opening as a function of the applied load, allowing to plot a graphic known as CMOD (Crack Mouth Opening Displacement) versus applied load.

As recommended by the standards API-5L and DNV-OS-F101, the thickness of each sample tested represented the total wall thickness of the pipeline. All specimens were obtained in accordance with specifications BS7448 (1991) and ASTM E1820-08 standards. It should also be noted that these standards require about the same test parameters, differing only in the equation for determining the value of CTOD. None of the tested CTOD specimens was fully broken at the end of the experiments. The fractured specimens were highly deformed which can be proved by shear lips shown in Fig. 6(a). The final breaking was carried out by tensile to obtain the fracture surfaces that are shown in Fig. 6. This indicated high toughness properties for this steel. After the CTOD tests carried out, an optical instrument (Profile Projector) was used for crack measuring from fracture surface. As can be seen in Fig. 6(a) and 6(b) the weld metal sample showed a front crack more irregular than the base metal sample. Despite of this, both samples were validated in accordance the standards tests of fracture mechanics.

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Figure 6: (a) base metal specimen crack surface after CTOD test; (b) weld metal specimen crack surface after CTOD test.

From the data obtained by the CTOD test machine, Fig. 7(a) and Fig. 7(b), was possible to set up the curve load [kN] versus displacement or CMOD [mm] for each sample tested as shown in Figure 7(c) and 7(d) . From this curve was determined the maximum load supported by the specimen (F) and the corresponding crack mouth opening displacement defined as (Vp). The area integral under the curve load versus CMOD gives the specified area (Ap).

A load-displacement curve like Fig. 7(a), 7(b), 7(c) and 7(d) showed a maximum load plateau, meaning that the crack propagation is still stable after maximum load. This situation occurs when the rate of strain hardening is exactly balanced by the rate of decrease in the cross section. However, the initiation of crack growth cannot be detected from the load-displacement curve because the loss of cross section is gradual (Anderson, 1995).

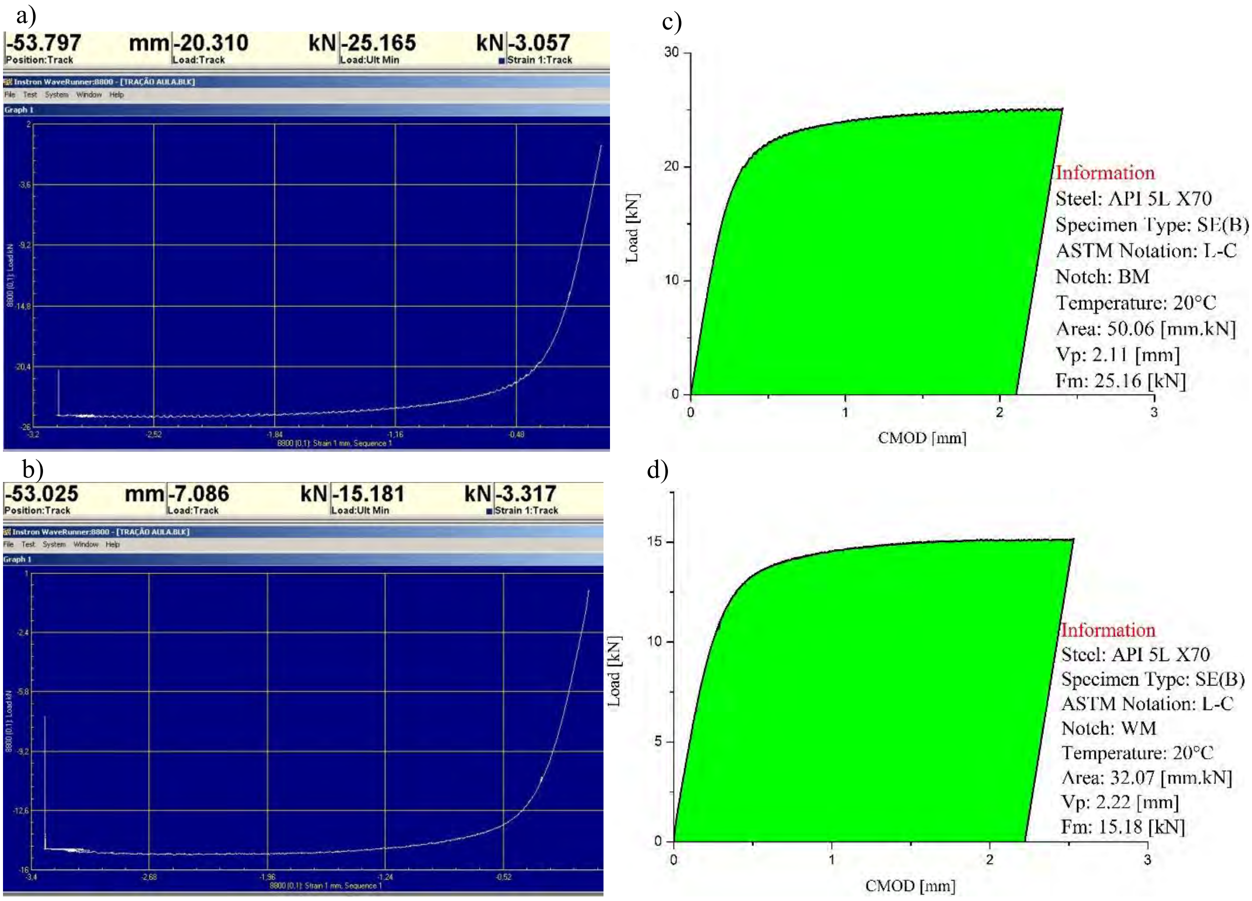

Figure 7: (a) Base metal curve Load [kN] versus strain [mm] provided by the CTOD test machine; (b) weld metal curve load [kN] versus strain [mm] provided by the CTOD test machine; (c) base metal curve load [kN] versus CMOD [mm]; (d) weld metal curve load [kN] versus CMOD [mm].

CTOD values presented in Tab. 4 were calculated taking the maximum load values from the graphic load versus displacement as a CMOD function. The parameters Fm and Vp were used to determine the CTOD by BS 7448 standard, whereas, Fm and Ap were used to determine the corresponding CTOD by ASTM E 1820-08 standard. Experimental results including the elastic and plastic components of CTOD for both specimens are listed in Table 4.

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Table 4. CTOD values determined by BS 7448 and ASTM E1820.

Standard	Sample	$(\boldsymbol{\delta_{el}})$	$(\boldsymbol{\delta_{pl}})$	$(\boldsymbol{\delta_{m}})$
BS 7448	Base Metal - BM	0.052	0.566	0.618
ASTM E1820	Base Metal - BM	0.053	0.602	0.655
BS 7448	Weld Metal -WM	0.039	0.438	0.477
ASTM E1820	Weld Metal -WM	0.038	0.457	0.495

Both samples showed a good toughness at the room temperature, in other words, the pipeline steel and its welded joint showed a high toughness in service conditions. Altogether, as shown in Fig. 7(b) and 7(d), both tested specimens in this condition have shown a high level of plasticity characterized by curves of increasing loads combined to high values of CMOD obtained. It can also be seen from the data in Tab. 4 whose CTOD plastic $(\boldsymbol{\delta_{pl}})$ for both specimens have shown a high value. According to the Fig. 7(b) and 7(d), the base metal specimen endured a higher load than the weld metal specimen; despite the weld metal has shown the highest value of CMOD. As shown in Tab. 4, δ(ASTM) tends to be bigger than δ(BS). It is also interesting to mention that the CTOD values obtained by BS 7448 (1991) and ASTM E1820-08 standard test method, even though both methodology have adopted different CMOD curve parameters to determine the CTOD, the results converged to a common value.

The fractograph in Fig. 8(a) and 8(b) (20 µm scale) was taken, respectively, from the stretch zone of base metal (BM) and weld metal (WM). The stretch zone is defined as transition region formed between the stable propagation and unstable crack propagation caused by the overload that takes the final break, and their formation is associated with the conditions of the fracture toughness of the material. As can be seen in Fig.8, both samples exhibited a large stretch zone that can be related their high toughness.

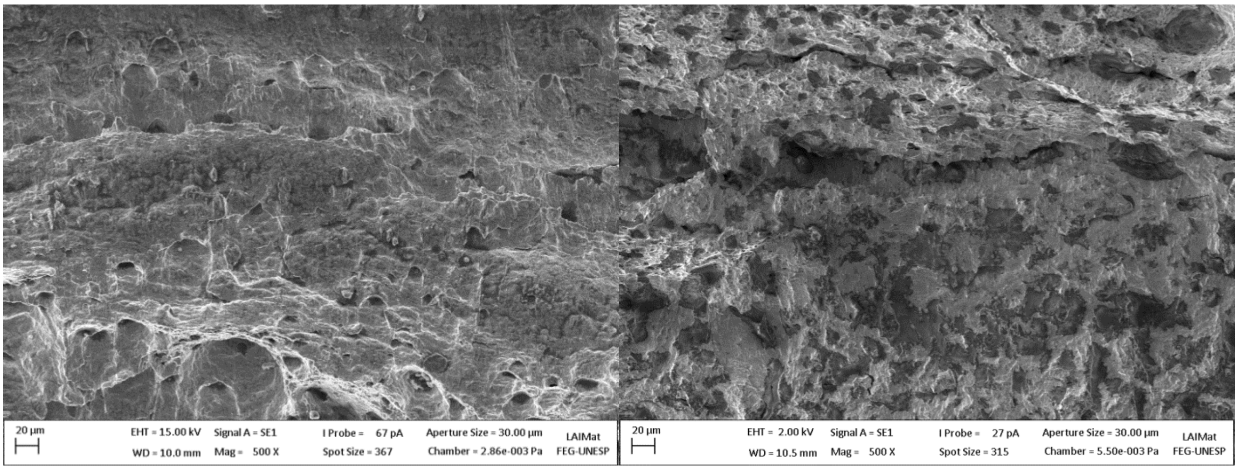

Figure 8: (a) Base metal stretch zone; (b) weld metal stretch zone.

Figures 9(a) up to 9(c) demonstrates the SEM micrographs of the centre of fracture surface of CTOD specimen extracted from base metal. It is clear that micrograph of BM fracture surface consist predominantly of dimples characteristics of slant shearing. The shape and size of dimples were directly related to the loading conditions and ductility of the material. Figure 9(a) showed tearing dimples as fracture features. Figure 9(b) showed local stretching and shallow tearing dimples. At high magnification, SEM micrograph shown in Fig. 9(c) large stretched holes around non-coherent inclusions. It can be noticed from the base metal surface features that evolution of the fracture mechanism was predominantly by shearing. This indicated high ductile properties for this steel. As shown in Fig. 9(d), although the weld metal fracture surface had less dimple morphology than the base metal, its presence is remarkable.

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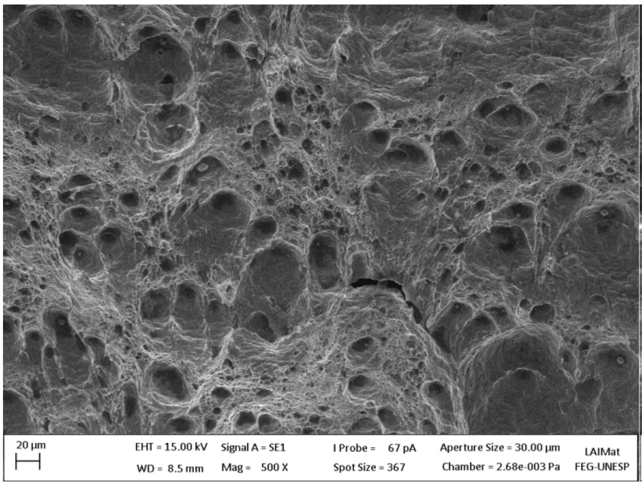
a)



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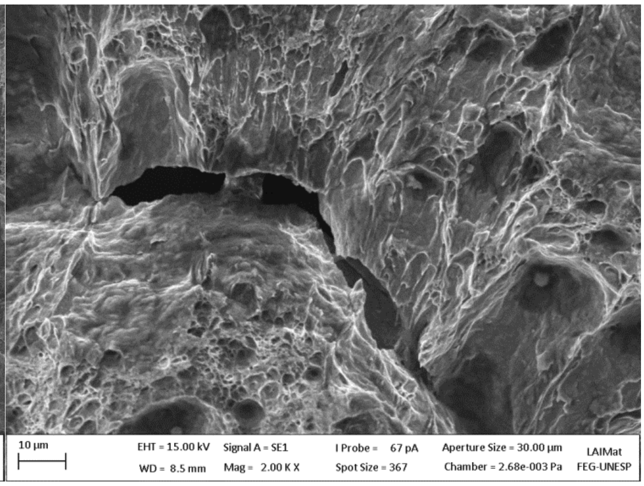

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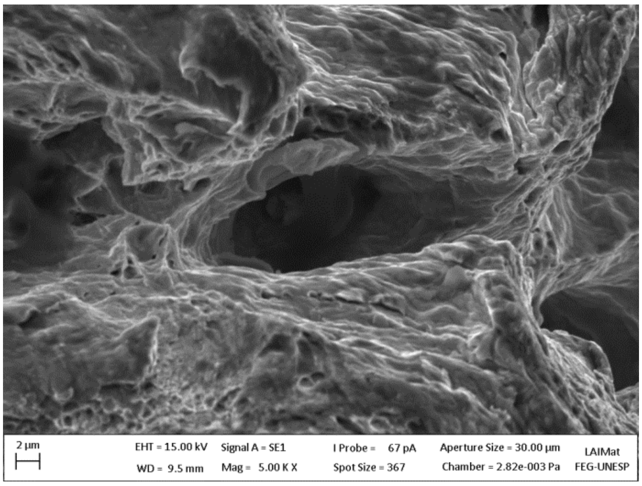

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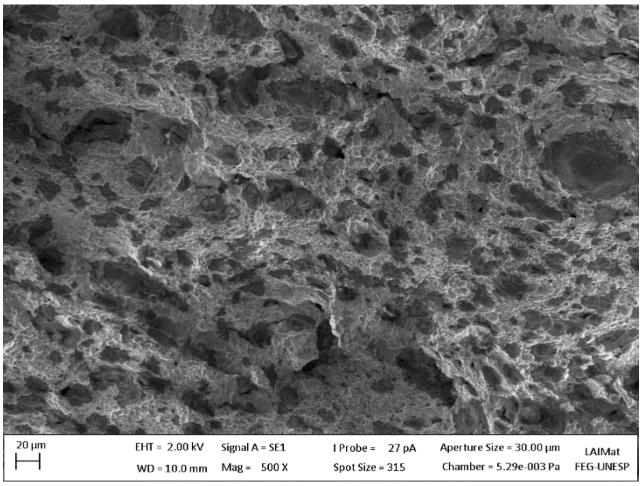

Figure 9: SEM fractographs of the centre of fracture surface taken from BM and WM. (a) BM with tearing dimples; (b) BM with local stretching and shallow tearing dimples; (c) BM with large stretched holes around non-coherent inclusions; (d) WM with dimples.

4. CONCLUSIONS

As can be seen in the introduction of this work, a considerable amount of research has been undertaken on high strength steels in recent years providing new data to support onshore and offshore applications for oil and gas industry.

The fracture toughness of specimens extracted from API 5L-X70 pipeline girth welded joint obtained by welding technique GTAW (Gas Tungsten Arc Welding) in the root pass and welding process FCAW (Flux Cored Arc Welding) in the subsequent passes (filling and finishing) was investigated. Experimental CTOD tests on base metal and weld metal specimens taken from pipeline were carried out. Based from the present investigation results, the main conclusions can be summarized in the following:

1. The API 5L X70 steel possess good mechanical properties since both samples showed yield strengths over 485 MPa (70 ksi) and tensile strength over 570 MPa (82 ksi), satisfying the strength requirement of API X70 grade pipeline steels set by API 5L 44th .

2. Through tensile tests the overmatching condition was proven since both samples were fractured at the base metal. Current practices and codes of manufacture as ASME and AWS require the overmatching conditions, thereby the welding procedure specification adopted it was good.

3. According to the CTOD results, both samples showed a good toughness at the room temperature. The good fracture toughness can be observed by high CTOD values. The base metal showed a higher CTOD value than the weld metal. This feature can be observed on load versus CMOD curve, where the base metal had a bigger plastic area under the curve than weld metal.

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4. The selection of welding parameters was made on the basis of good engineering experiences that can be proven by tensile and CTOD tests at room temperature. This work highlighted the importance of using a qualified welding procedure for performing quality welds while ensuring the properties of the fracture toughness of the weld metal.

5. CTOD tests were carried out based on fracture mechanics and the critical CTOD values in BS7448 were compared with those in ASTM E1820-08. It was found that the values of CTOD tend to converge to a common value, although, the CTOD obtained by BS7448 tends to give slightly smaller value of the critical CTOD than that evaluated by ASTM E1820.08.

6. The girth welding simulation carried out at 6G position to simulate field welding conditions was proven adequate for installation and joint of pipeline once the properties of weld metal were good as well as the base metal.

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